AR-009-903

DSTO-TN-0059

Methods of Early Fatigue Detection

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19971007 200

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ABSTRACT

This note presents a brief review of techniques which may be applied to the detection of the early manifestations of fatigue damage in metals and also introduces two new methods which at the time of the preparation of this note were the subject of feasibility investigations at AMRL. In the first of these new methods, the fatigue state of a structure is inferred from variations in the electrical resistance of a metal foil bonded to the structure and subjected to the same loading history. The second method involves the infusion of radioactive hydrogen (tritium) into a structure that may contain fatigue damage. Damaged parts of the structure act as preferred trapping sites for the tritium, and these may be detected by the emission of beta radiation from the decay of the trapped tritium.

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Methods Of Early Fatigue Damage Detection

EXECUTIVE SUMMARY

Effective aircraft fatigue management requires that structural defects are detected before they reach critical dimensions. However this requirement cannot always be satisfactorily met by conventional non-destructive inspection techniques because of practical limitations on the smallest defect size they can reliably detect. A number of existing methods are presented in this note that are capable of detecting early fatigue damage such as microcracks and various manifestations of the localised plastic deformation that is the precursor to microcrack formation. The detection of these types of damage can provide an early indication of the areas in a structure that may be prone to macrocrack formation. As well as reviewing existing methods of early fatigue damage detection, this note also describes two new methods that are currently the subject of feasibility investigations being conducted at AMRL. The concept of a mean-stress gauge is introduced, whereby the fatigue state of a structure is inferred from variations in the electrical resistance of a metal foil bonded to the structure and subjected to the same loading history. The second method involves the infusion of radioactive hydrogen (tritium) into a structure that may have developed fatigue damage. Damaged parts of the structure act as preferred trapping sites for the tritium, and these may be detected by the emission of beta radiation from the decay of the trapped tritium.

CONTENTS

1. Introduction

High levels of uncertainty in current fatigue-life prediction techniques, and the often catastrophic nature of fatigue failure, drive the continuing effort to develop techniques for detecting and characterising fatigue damage. The series of Comet aircraft disasters in the early 1950's (see Stewart (1994)) serve as a reminder of the consequences that can ensue when fatigue damage remains undetected. Disasters of this scale rarely occur nowadays largely as a result of the use of fatigue-tolerant approaches in the design of aircraft and the application of fatigue-crack inspection procedures to operational aircraft.

Currently, the objective of operational aircraft safety is met by the 'safety-by-inspection' (SBI) approach (e.g., Finney (1994)). This comprises the application of non-destructive inspection (NDI) techniques to the task of defect detection, and analyses based on fracture mechanics to decide on issues of structural integrity. Conventional NDI techniques, however, are not always capable of detecting defects to the requirement of the SBI approach. Figure 1 contains a chart based on the Engineering Sciences Data Unit on non-destructive examination (ESDU (1991)) showing data on defect resolution limits for the more popular NDI techniques. It is evident from this chart that even when implemented under ideal conditions, the most sensitive method is incapable of reliably detecting defects less than about 0.8 mm in characteristic size. Whilst this defect detection capability is sufficient for the majority of situations demanding NDI, there are nevertheless some circumstances where this capability is inadequate. For instance, it was reported by Clark and Arnott (1991) that unstable crack growth occurs in the F/A-18 FS488 bulkhead at crack depths of about 5 mm, and that to satisfy safety-by-inspection principles this would require cracks in the bulkhead to be detected at sub-millimetre sizes. The authors went on to note that available non-destructive techniques (ultrasonic, dye-penetrant, eddy-current and acoustic emission) had not demonstrated this capability.

This note presents an investigation into methods of early fatigue-damage detection that, at least in principle, are far more sensitive than conventional NDI methods, considered here to comprise those shown in Fig. 1. Existing methods of early fatigue-damage detection are reviewed, and two new techniques that are currently the subject of feasibility studies are also described. The note is structured in two sections dealing separately with (i) techniques that involve the direct inspection of the structure of interest, and (ii) techniques that involve the application of a fatigue 'sensor' to the structure. A list of the methods to be considered, categorised in this manner, is given in Table 1.
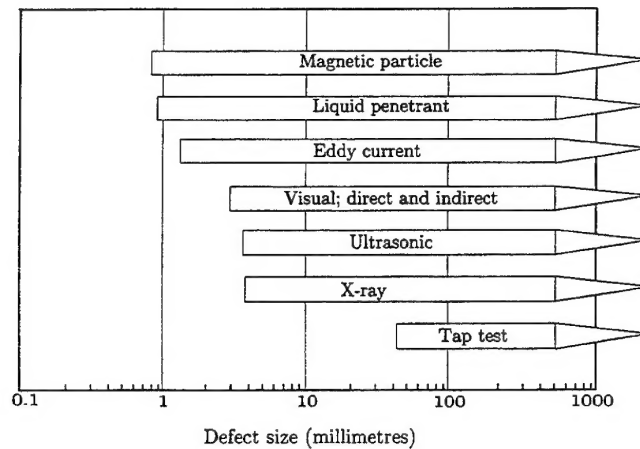
Figure 1. Defect detection capabilities of some conventional NDI techniques. (ESDU (1991))

Table 1. Methods of fatigue damage detection considered.

Fatigue Sensors	Direct Inspection
Electrical Resistance	Alternating Current Potential Drop
Surface Roughness	Barkhausen Noise
Martensitic Transformation	Positron Annihilation
Fatigue Fuses	Ultrasonic Rayleigh Wave
Oxide Film Sensor	Acoustic Microscopy
Mean Stress Gauge	Ultrasonic Attenuation
	Acoustic Emission
	Tritium Autoradiography

2. Fatigue Sensors

2.1 Electrical Resistance Gauges

All metals exhibit a resistance to electrical current (see Rose *et al* (1966)), and the resistivity, ρ, can be generally expressed as the sum of two components,

$$\rho = \rho_T + \rho_r.$$

The first term, ρ_T, is due to the scattering of electrons by the thermally-induced vibratory motion of the lattice, and is accordingly termed the thermal component. Occurring in all conductors and at all temperatures except absolute zero, this form of resistance is not directly dependent on the fatigue state. The second term, ρ_r, is termed the residual resistivity and relates to electron scattering from imperfections in the crystalline structure, such as point (vacancies and inclusions), line (dislocations) and surface defects (grain boundaries and stacking faults). The formation and multiplication of particularly the former two imperfection types occur at a relatively early stage in the fatigue process, and consequently changes in residual resistivity are often observed in a metal undergoing cyclic loading well before the formation of a crack.

Fatigue monitoring applications relying on the relationship between resistivity and fatigue damage were realised at least thirty years ago. Harting's *-S/N- Fatigue-life Gage* (Harting (1966)) is the best known example and was at the time of its inception considered sufficiently viable to attract commercial interest. It was claimed to provide a direct means of measuring cumulative fatigue damage in a structure to which it was bonded. Harting found that he could relate the change in the electrical resistance of the gauge to fatigue-loading parameters according to the simple expression,

$$\frac{\Delta R}{R} = K(\varepsilon_p - \varepsilon_o)N^h,$$

where ΔR is the change in resistance R, N is the number of applied cycles, h is a constant (≈ 4), ε_p is the peak value of the cyclic strain, and ε_o is the endurance limit strain, below which no permanent resistance change occurs.

The material chosen for the gauge construction was an annealed constantan alloy. Nickel-copper alloys like constantan have a resistivity that depends strongly on the amount of accumulated fatigue-damage. Charsley & Robins (1975) proposed an explanation for the strong dependence in terms of the interaction of dislocations with nickel clusters present in the alloy. These clusters generally improve the conductivity of the alloy and so their comminution by dislocation motion usually (though not always) results in an increase in resistivity. The changes are slight, usually less than 3% just prior to fracture of the alloy, though in the context of resistivity changes in metals induced as a result of fatigue damage, this level is comparatively high.

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The study by Charsley & Robins is one of a series of investigations carried out by these authors on the effects of fatigue on electrical resistance. In an earlier study, Charsley & Robins (1974) examined the resistance changes induced as a result of fatigue damage in nominally pure polycrystalline copper with an emphasis on the influence of load amplitude, frequency of loading, number of cycles and grain size. The change in resistance as a function of the number of fatigue cycles is shown in Fig. 2 and can be separated into two regions where the underlying physical mechanisms are different. In the first region, the operating mechanism of fatigue-damage is one of the formation and multiplication of dislocations and vacancies and this leads to the observed gradual increase in resistivity. The second region is distinguished by a much higher rate of change of resistance, and the mechanism here was identified as intergranular cracking. Overall, an increase in the load amplitude was observed to have the effect of increasing the rate of change of the resistance with respect to the number of load cycles. Interestingly, the final value of resistance before the onset of intergranular cracking was found to be relatively independent of the load amplitude. Frequency of loading and grain size were reported to have little influence on the resistance change.
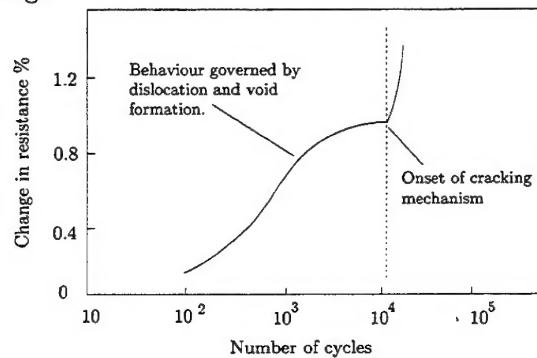
Figure 2. Typical resistance change in polycrystalline copper due to fatigue cycling.

The behaviour depicted in Fig. 2 is not typical of all metals. In Cu-Ni alloys for example, Charsley & Robins (1975) and Charsley & Shimmin (1979) found the characteristics of the resistance change to depend on the nickel content. Figure 3 shows a comparison of the approximate resistance change due to fatigue of two Cu-Ni alloys of different composition, Cu – 20% Ni and Cu – 51% Ni.

Figure 3. Typical resistance change in Cu-Ni alloy due to fatigue cycling.

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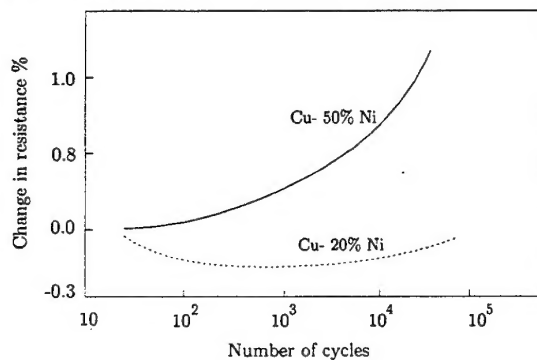A clear difference in behaviour is apparent in the early stages of fatigue; the alloy of lower nickel content initially decreases in resistance, whilst that of higher nickel content increases. Somewhat curiously, both behaviours arose via a single dominant mechanism involving the comminution of nickel clusters by mobile dislocations (Charsley & Robins (1975)). It was later reported (Robins & Charsley (1976)) that resistance changes in these alloys are dependent upon grain size, a feature not found in polycrystalline copper.

Resistance changes which occur due to fatigue are generally quite small and can be diffi- cult to measure reliably. Apart from the general difficulties involved in measuring small absolute changes, one has the additional problem of separating the fatigue-induced resis- tance changes from other changes, such as those occurring due to ambient temperature variations. Constable and Sahay (1992), in studying soldered joints in printed circuit boards subjected to cyclic loading, found that such difficulties could be avoided by mea- suring the resistance change at the fundamental frequency of loading as well as at its harmonics. Because of the persistent nature of the excitation the method has good noise rejection characteristics and since ambient temperature fluctuations are unlikely to occur exactly at, or integer multiples of, the frequency of loading, temperature effects are re- moved. Experiments revealed the second harmonic response to be especially sensitive to the effects of fatigue, Constable and Lizzul (1995).

2.1.1 Polymer-based Electrical Resistance Fatigue Gauges

Much larger changes in fatigue-induced electrical resistance are found for a class of ma- terials known as conductive polymers, Dally & Panizza (1972). Here, the polymer was composed of many randomly-distributed highly-conductive graphite particles suspended in an epoxy matrix. The resistivity of the combined structure is a function of the volume fraction of graphite and, in particular, the contact area between the graphite particles. During fatigue loading, cyclic deformation causes the graphite particles to rub against each other thereby increasing their contact area, and thus permanently decreasing the re- sistivity of the mixture. In experiments performed by Dally & Panizza (1972), reductions in resistance of the order of 40% were observed before failure of the epoxy matrix.
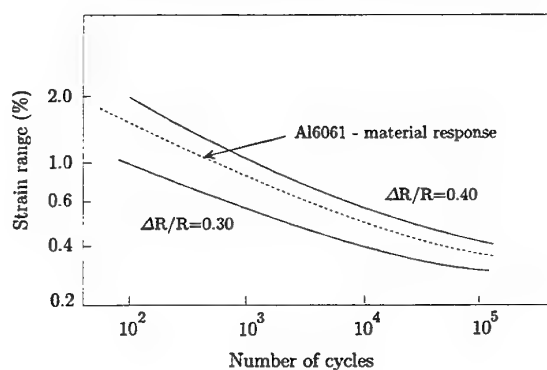

Figure 4. S-N curve for Al6061 and curves of constant $\Delta R/R$ for polymer fatigue gauge. ΔR is the change in resistance from an initial value of R

In a later paper, Panizza & Dally (1973) examined the application of the sensor to fatigue monitoring of structures. Polymer gauges were bonded to a structure which was then

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subjected to constant-amplitude fatigue cycling. They found that the change in resistance of the polymer gauge was strongly correlated with the fatigue failure of the structure for certain metals. The correlation was expressed in terms of the similarity between the S-N curve for the metal and the S-N curve for the polymer gauge at a constant $\Delta R/R$. This is depicted in Fig. 4 in which an S-N curve for Al6061 is seen to be approximately parallel to curves of constant $\Delta R/R$ for the polymer fatigue gauge. The curve for $\Delta R/R = 0.37$, not shown in the figure, was reported by the authors to coincide with the Al6061 S-N curve.

The agreement in the case of an Al6061 alloy implies that the same gauge may not perform as well for other materials. Indeed, in applying these gauges to Al2024, Panizza & Dally (1973) found the gauge behaviour to be a rather poor indicator of fatigue failure. However, the authors reported that improvements in the performance of the gauge could be achieved by reducing the strain range to which it was subjected. These reductions were accomplished by varying the orientation of the gauge relative to the strain field.

Variable amplitude loading presents a more difficult proposition. Panizza & Dally (1973) concluded that under these conditions the polymer gauge could adequately predict failure if two rather stringent conditions were met: (i) the structural material followed Miner's damage law, and (ii) the gauge and structure were perfectly matched.

2.2 Surface Roughness Gauge

The plastic deformation of a highly polished specimen can often lead to a noticeable surface roughening due to the impingement of dislocations on the specimen surface. Shown in Fig. 5a is a polished mild-steel specimen containing a fatigue crack, and adjacent to and extending from the crack, a region shaped like a hand which is effectively the zone of monotonic plastic deformation caused by the application to the specimen of a tensile load normal to the crack propagation direction. In the case depicted in this figure (see Rajic 1995), the observed surface roughening was exploited to identify the extent of a plastically deformed region. However, the phenomenon has also been proposed as a useful means of fatigue characterisation. In a recent paper by Nagase et al (1995), thin aluminium foils were bonded to a fatigue-loaded structure with the view of correlating the evolution of surface roughening in the foil with the fatigue history of the specimen. Under constant stress-amplitude loading, the relationship between the measure of surface roughness, Ra, stress amplitude, σ, and number of loading cycles, N, was expressed as,

$$Ra = \frac{1}{k_o}\sigma^{\alpha/2}N^{1/2} + m,$$

where α, k_o and m are material constants. Surface roughness measurements were made using an infrared-based profilometer. Figure 5b shows a series of S-N curves for constant values of Ra. To enable the gauges to be used under variable stress-amplitude loading, the authors developed the concept of an 'equivalent' stress, which is defined as the constant amplitude stress that results in the same degree of surface roughness, and may be expressed as,

$$\sigma_{eq} = (\sum \sigma_i^{\alpha} N_i / \sum N_i)^{1/\alpha},$$

where N_i is the number of stress cycles in a loading block at stress amplitude σ_i. The equivalent stress is determined from experiment according to the expression,

$$\sigma_{eq} = \{(Ra_n - m)^2 k_o^2 / \sum N_i\}^{1/\alpha},$$

where Ra_n is the roughness measured after $\sum N_i$ cycles. This expression was applied to experimental data with mixed results. In tests involving only a few stress-amplitude variations, the expression failed to describe the gauge behaviour well because of its disregard of the ordering of these variations (i.e. high-low & low-high). However, with increasing numbers of stress-amplitude variations, the effect of ordering diminishes and the expression under these conditions was found to provide a satisfactory description of the gauge behaviour.
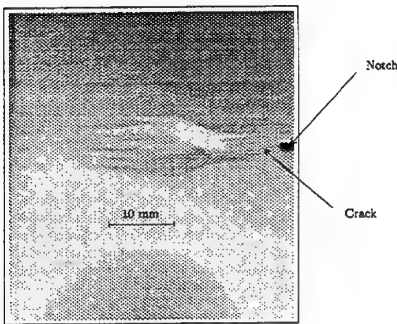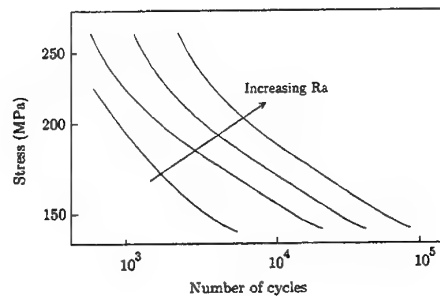

Figure 5a. Plastic zone.

Figure 5b. S-N curves for constant Ra's.

2.3 Martensitic Transformation Fatigue Sensor

Scott (1977) describes a fatigue sensor that exploits the tendency of silver-zinc alloy to change colour in response to fatigue loading. The colour change is reported to occur due to the silver-zinc film undergoing a martensitic phase transformation in response to cold work induced by cyclic loading. Since it exploits colour variations, this gauge has a unique advantage among fatigue sensors in that it should enable one to gain a qualitative indication of the fatigue state of the underlying structure by simple visual inspection. A more quantitative measure of the colour change, which is stated as being from pink to silver, can be obtained with a spectrometer. The sensor is shown schematically in Fig. 6.
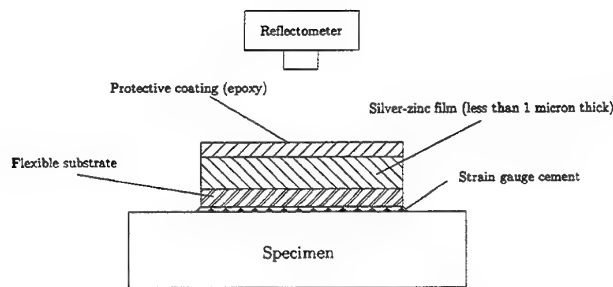
Figure 6. Colour Displaying Fatigue Sensor, from Scott (1977).

Very few technical details about the gauge were given and so it is not possible to comment on its efficacy.

2.4 Fatigue Fuses

One of the earliest fatigue monitoring devices to be patented was the *Fatigue Indicator* invented by DeForest (1948). This simple device comprises a thin wire or ribbon which has a fatigue life that is a known fraction of the life of the member material being monitored. The integrity of the sensor is assessed by continually measuring its electrical resistance, with failure indicated by a sudden increase in resistance due to the loss of electrical continuity. Rosenfeld & Scheindlinger (1972) made brief mention of an attempt to utilise a 'crack-detection wire' as a fatigue monitor and cited significant problems with the reliability of the method even under laboratory conditions.

A modern adaptation of DeForest's idea can be found in the *Fatigue Fuse* device marketed by Tensiodyne Scientific Corporation. The fuse is made from a thin sheet of the same material as that of the structure being monitored, and comprises a number of coupons, each providing a stress concentration of different but known severity. When subjected to the same strain history as that imposed on the member being monitored, the coupons progressively fail prior to the member, thereby giving a warning of the structure's impending failure. By having several coupons in the fuse, each with a different stress concentration,

it is possible to estimate the residual life of the structure at several stages in its life. Figure 7 shows a basic outline of the fuse. The coupons presented in this figure are derived from patent held by Tensiodyne (1986) and represent only a few of the many shapes available. Note that only the hatched portion of the fuse is bonded to the structure.
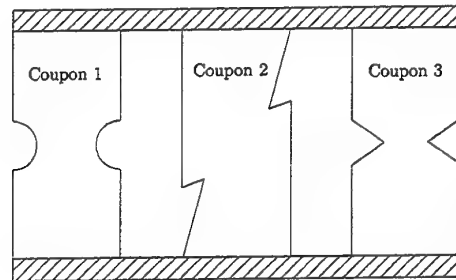

Figure 7. Tensiodyne fatigue fuse.

Slight variations to the concept are covered in subsequent patents, see Tensiodyne (1987, 1993, 1994 & 1995). In order to develop a strain concentration at the notch root, it is necessary that these fatigue fuses are bonded only over a small strip at either end as shown in Fig. 7. In so doing, the gauge encounters only a spatial average of the strain experienced by the underlying structure, which could compromise the performance of the gauge in applications involving large strain gradients. Another possible drawback due to the localised nature of attachment may be found in circumstances where the sensor is to be applied to a curved surface, and in particular on a concave surface, like that at the inside of a hole. Under these conditions the gauge could presumably experience out-of-plane displacements which bear no relation to the strain experienced by the structure.
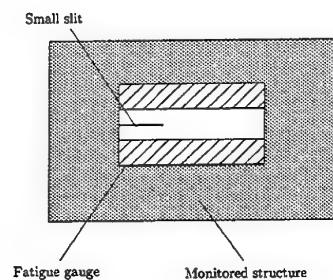
Figure 8. Fatigue gauge from Smith (1976).

Smith (1976) developed and patented a device similar to the *Fatigue Fuse*, which, instead of having a notch, has a small slit, see Fig. 8. The principle is the same, that is the accumulation of damage in the device, in this case indicated by progressive crack growth, is used to infer information about the fatigue state of the structure. Geissler & Gallagher (1983) describe an investigation carried out for the USAF into the application of this type of gauge to aircraft fatigue-damage tracking. They concluded that the proposed

gauge designs were unsuitable for this purpose because of unacceptable variability in experimental results under spectrum type fatigue loading. The cause of the variability was not stated though it was determined that the effects of variations in material properties and gauge dimensions were insufficient to provide an explanation. A possible reason for the variability may be conjectured. For there to exist a good correlation between the fatigue behaviour of the gauge and that of the structure there needs to be a certain degree of similarity between the stress-state conditions at the crack tip in the sensor and the conditions in the structure at the location to be monitored. Under variable amplitude loading conditions, the influences of crack-tip blunting and overload-induced residual stresses at the crack-tip would make that similarity hard to obtain. Furthermore, it is suspected that such effects would be difficult to eliminate using calibration methods.

2.5 Oxide-film Sensors of Fatigue

The application of oxide film methods to the quantitative assessment of fatigue damage is described in Baxter (1977, 1979, 1982, 1983, & 1984). Two methods are used, the exoelectron and the gel electrode methods. Both exploit the rupture of an oxide layer on a metallic surface to detect surface fatigue damage in the metal, and differ mainly in the way that the rupture is detected. Baxter describes the exoelectron method as detecting fatigue damage by using the preferential emission of photoelectrons (excited by incident U.V. radiation) from the metal surfaces freshly exposed by microcracks in the surface oxide film. To prevent reoxidation of the microcracks, and therefore maintain the preferential emission of photoelectrons, the technique needs to be applied in a vacuum. The obvious limitation this places on its practical use led to the development of the gel electrode method. Here, microcracks in the oxide are detected by contacting the specimen with a film of gel composed of potassium iodide and starch. When a voltage pulse is applied through the gel, a corrosion current is formed which flows preferentially to the microcracks. Chemical reactions caused by the current render a change in colour in the gel which provides a visible indication of the location of the microcrack.

For the surface oxide layer to function as a reliable and quantitative discriminator of fatigue of the underlying metal, Baxter (1982) states that the fracture properties of the film must be consistent and reproducible from specimen to specimen. This is most easily satisfied by 'manufacturing' the oxide layer, as Baxter achieved by anodizing specimens in a 3% solution of tartaric acid at a potential of 10 volts. The resulting oxide layer was 14 nm thick, about 10 nm thicker than that which occurred naturally. The difference in thickness is important for the successful implementation of the gel electrode method, as otherwise, natural reoxidation in the microcracks would render them invisible. Very thick oxide layers (100 nm) were not recommended for the reason that they can rupture independently of the deformation of the substrate metal.

Using the gel-electrode method, Baxter (1982) found that fatigue damage in a number of grades of aluminium alloy (including 7075-T6, 2024-T3 and T4, 6061-T6 and 1100-0) could be detected as early as 0.2% of the fatigue life. In addition, it was found that the flow of charge from the cracks in the oxide layer provides a quantitative measure of the severity of fatigue damage and could provide a basis for the early prediction of fatigue life.

One should point out that our definition of this technique as a 'fatigue sensor' is not altogether clear cut, since the method involves, to some degree, the direct inspection of

the structure. It was decided that the reliance of the gel-electrode method (which appears the more practicable of the two) on the application of a medium to deduce the relevant fatigue damage information, and the fact that the detected damage is in the oxide film rather than in the metal itself, are probably reason enough to warrant its inclusion in the fatigue sensor category.

2.6 Mean-Stress Gauge

Relating the information derived from a fatigue sensor to the fatigue damage in the structure to which it is applied is difficult if the sensor and structure possess different mechanical properties. This led to the authors developing the concept behind the mean-stress gauge. The gauge is currently the subject of an experimental feasibility investigation and the results will be reported at a later date. A brief description of the concept follows.

It is well known that the superposition of a tensile mean stress on a fluctuating load has a detrimental effect on fatigue life. Furthermore, it is possible to estimate the reduction in life from S-N curves which include R-ratio (mean stress) variations. Given this, it should in theory be possible to attach to a structure a pretensioned foil made of the same material, such that it breaks at a predetermined (from S-N curves) number of fatigue cycles before the structure, and thereby gives warning of the structure's impending failure. The fatigue state of the foil could be tracked by continuously measuring its electrical resistance; failure would obviously be indicated by a large increase in its resistance. This is however a rather crude application of the concept. One will recall from earlier discussions that the residual resistivity of a metal is generally dependent upon its fatigue state and that changes in this resistivity occur well before the formation of a macrocrack. Hence, if the resistance measurements were to be made with sufficient precision to detect changes in the residual resistivity, it should be possible to know the fatigue state of the foil (and therefore the structure) continuously and from an early stage in its life. The basic elements of the gauge are shown in Fig. 9.
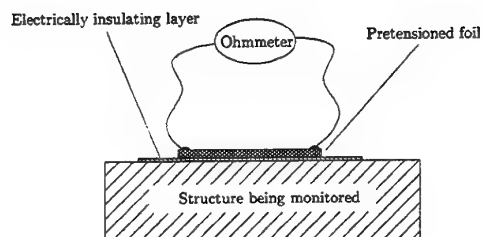

Figure 9. Mean-stress Gauge.

3. Direct Inspection Methods

3.1 Alternating Current Potential Drop (ACPD)

In the ACPD method, a high frequency constant-amplitude current is applied to a specimen resulting in the establishment of an electric field distribution that is influenced by defects present in the specimen. By measuring variations in the potential drop between two locations on the specimen surface during fatigue cycling, the presence of cracks along the conductive path may be established and the size of these cracks determined. In contrast to the older direct current potential drop method, the current in the ACPD method is confined to the surface regions of the material through the skin effect and is therefore more sensitive to surface breaking cracks.

Dai and co-workers (1993) used the ACPD method to investigate the initiation and growth of fatigue cracks in titanium alloys and established that defects as small as 50 μm in depth could be reliably detected. In the experiments conducted by Dai et al (1993), the current supply leads and the potential-drop measurement leads were spot welded to the specimen surface, presumably to avoid contact irregularities that would otherwise occur for less intimate contacting methods. No comment was made on the reliability of other contacting methods nor of the influence of the spotwelding on the fatigue behaviour of the monitored specimen. One could reasonably suspect that spotwelding may influence the fatigue behaviour of a metal either by providing a crack initiation site due to weld pitting or by altering the microstructure in the heat affected zone. The use of small leads (in Dai et al (1993), 0.5 mm and 0.127 mm diameter wires were used for the supply and sensing leads respectively) and the attachment of these leads outside the fatigue critical location should help in avoiding these potential problems.

3.2 Barkhausen Noise

Ferromagnetic materials are composed of regions, called domains, where the magnetic-dipole-moment density or magnetisation is constant. The application of a small external magnetic field enables the domains favourably orientated with respect to the field to expand at the expense of domains which are less favourably orientated. This rearrangement entails the movement of the 'walls' separating the domains, which can occur smoothly but for the presence of imperfections such as dislocations, voids and defects. These defects pin the domain walls until sufficient energy is supplied to overcome them, at which point the domain wall moves suddenly, resulting in a sudden change in magnetisation. If an induction coil is placed near the source of these sudden changes in magnetisation, seemingly random voltage pulses are observed, hence the reference to the term *noise* in the name of the technique.

A number of studies have revealed that the Barkhausen effect depends on the fatigue state. Karjalainen & Moilanen (1979) found that the level of Barkhausen noise decreased as a function of the number of loading cycles applied to a low-carbon steel. Tiitto (1990) later suggested that the effect could be used to assess the residual life of a component, and commented on the practicalities of the method, citing the commercial availability and good portability of the necessary equipment.

Ruuskanen and Kettunen (1987) describe a device that is purported to enable relatively quick measurement of the fatigue limit of a material. The process involves applying a constant magnetic field to a specimen that is subject to fatigue loading and measuring the Barkhausen noise as the amplitude of loading is gradually increased. The load at which a maximum value is reached is said to correspond to the fatigue limit of the material. This presumably occurs as a result of the onset of increased dislocation activity at the fatigue limit stress.

The technique is unlikely to find widespread application to aircraft structures because of the extensive use of non-ferromagnetic materials in their construction. However, some aircraft contain steel components that require NDI (i.e. the wing carry-through box in the F-111), and these could be assessed using this technique.

3.3 Positron Annihilation

A positron is an antiparticle of the electron. When introduced into a material, positrons are annihilated with electrons to produce gamma-ray energy. The annihilation process is dependent upon the structure of the material into which the positrons are injected. Notably, the defect structure of a material is known to influence certain properties of the emitted gamma radiation, like the angle separating the emitted gamma-ray pair, the life-time of the positron in the material, and the energy of the gamma-rays (see Seigel (1986) and Reno (1986)). These may all be measured and exploited as a means of characterising defects introduced as a result of fatigue cycling. Coleman et al (1982) for instance, applied positron annihilation techniques to specimens of titanium alloy subjected to fatigue cycling and found that measurements of the annihilation spectra were sensitive to defects produced by processes of plastic deformation which precede the formation of fatigue cracks. It is unclear how amenable the technique is to field application. Much of the existing literature on the application of positron annihilation to fatigue characterisation is concerned with the laboratory-based investigation of the micromechanics of the fatigue damage accumulation process (see Coleman et al (1977 a,b) and Grobstein et al (1991)). It therefore provides little insight into issues of practical implementation. It is suspected, however, that the requirement of gamma-ray detectors and positron sources may hinder the application of the technique to practical fatigue problems.

3.4 Ultrasonic Methods

Conventional ultrasonic inspection involves the detection of acoustic energy reflected from internal defects – the so-called pulse-echo method. In its customary guise this method has a defect resolution capability of approximately 3 mm as indicated by the diagram in Table 1. However, other ultrasonic methods exist that are capable of detecting significantly smaller cracks and in a few cases are capable of detecting the damage that occurs prior to the formation of cracks. These methods are now described.

3.4.1 Ultrasonic Rayleigh Wave Detection

Rayleigh waves are surface waves characterised by displacements which decay exponentially with depth and are therefore most suited to the detection of fatigue damage concentrated on the surface of a specimen. Hirao et al (1993) investigated the small crack fatigue

behaviour in 7075-T651 aluminium using the ultrasonic Rayleigh-wave reflection technique and found that fatigue cracks of depth as small as 0.1 mm could be routinely detected using equipment claimed to be convenient to use, portable and inexpensive. Acoustic reflections from grain boundaries in the material were reported to have a significant influence on the detectibility of smaller cracks. However, by employing a frequency-domain signal processing technique, the authors were able to improve the detectibility threshold to about 60 microns.

An investigation by Clark *et al* (1987) found the technique to be quite unreliable in detecting tightly-closed cracks and concluded that the ACPD method (§3.1) was superior in this respect. However, partially open cracks can be detected, and moreover, it is possible to assess the extent of closure by studying the frequency content of the reflected Rayleigh waves. Only the higher frequency components, which travel at greater depth beneath the surface, stand a chance of impacting upon the open section of the crack.

3.4.2 Acoustic Microscopy

In acoustic microscopy, high-frequency acoustic waves focused through a suitable lens and a fluid couplant are used to characterise the structure of a material. Acoustic microscopes may be operated in a continuous wave mode by which images of the surface defects may be obtained by Rayleigh wave reflection. Pulsed acoustic excitation is used for time-resolved measurements which enable the sub-surface structure of defects to be characterised from the time-of-flight of the returned acoustic pulses. Knauss and co-workers (1993) found cracks of 30 μm depth and 80 μm length in an Al–Li 8000 alloy using time resolved acoustic microscopy, and later Zhai *et al* (1994) were able to resolve cracks with depths as small as 17 μm in PSB's in an aluminium single crystal.

3.4.3 Ultrasonic Attenuation

Ultrasonic attenuation refers to the loss of a portion of the energy transported by a stress wave propagating through a structure. Energy dissipation may result from thermoelastic heating, grain boundary scattering, point defect scattering, and dislocation damping. The latter three mechanisms will reflect upon the level of fatigue-damage present in a structure and so the degree of ultrasonic attenuation through such a structure provides an insight into the state of fatigue damage. Ultrasonic attenuation has the distinction of being the first ultrasonic technique to be used in a fatigue monitoring role, Green (1979).
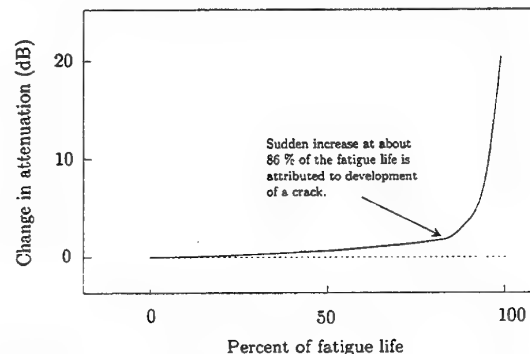
Figure 10. Schematic of an ultrasonic attenuation response for Al7075-T6 alloy

A representative plot of ultrasonic attenuation as a function of the number of loading cycles is shown in Fig. 10, which depicts a similar behaviour to that in Mignogna *et al* (1980), and relates to a fatigue test on 7075-T6 aluminium alloy. Although the attenuation is seen in this figure to increase in the early stages of fatigue, this behaviour is not observed in all cases. Depending on the material composition, loading conditions and temperature, the attenuation may actually decrease (Joshi & Green (1975)). For a detailed treatise on the relationship between dislocations and ultrasonic attenuation, the reader is referred to Nabarro (1987).

An interesting result was found by Mignogna *et al* (1980), who applied ultrasonic attenuation techniques to the characterisation of the fatigue state of an Al7075 alloy. A reliable indication of the fatigue state could be gained from the rate of change of attenuation with respect to time at a constant loading frequency. The authors found that when the rate of ultrasonic attenuation change had reached 0.1 dB/min, the material had expended about 90% of its fatigue life.

Burke & co-workers (1994) describe a novel approach by which the presence of a distribution of small similarly-orientated surface-cracks may be detected using acoustic attenuation and eddy current techniques. In the former case, cracks are detected by the anisotropy they cause in the attenuation of Rayleigh waves generated by a line-focused laser-ultrasonic source.

3.4.4 Acoustic Emission

Acoustic emission occurs as a consequence of dynamic processes in a structure. Mechanisms that may give rise to such emissions include dislocation formation and motion, crack propagation and crack-face rubbing. The primary factor limiting the application of the method appears to be the difficulty in separating the acoustic emission caused by dislocation movement, crack formation and propagation, from extraneous acoustic noise. This noise can and often does lead to a high rate of false defect-indications (see Horak & Weyhreter (1977)). However, the reliability of defect detection can be improved with the aid of signal processing techniques. Scala and co-workers (1992) for instance were able to isolate acoustic emission events arising from cracking in a fatigue-cycled F/A-18 bulkead in an acoustically noisy environment by extensive post-processing of acoustic emission data.

3.5 Tritium Autoradiography

The application of radioactive isotopes to fatigue crack detection was demonstrated in the early 1950's during the Comet aircraft accident investigation. Waterton & Hewat (1955) reported that radioactive isotopes injected into aviation fuel consumed in the engines of a Comet aircraft were later detected, somewhat serendipitously (the intended aim of introducing the isotopes was to locate points of leakage in the fuel tanks), in a small crack in one of the combustion chambers. Without obvious reason, the development of this application seems to have been largely ignored by the NDI community. A possible deterrent to its development may be the health and safety aspects relating to the handling and use of radioactive isotopes. However this seems an unwarranted concern in view of the almost routine use of tritium, a radioactive isotope of hydrogen, in the study of hydrogen embrittlement. The technique proposed here to detect fatigue damage

radioactive isotopes is an adaptation of an existing autoradiographic technique used in the investigation of hydrogen embrittlement. The adapted technique, in principle, involves the infusion of tritium into the damaged structure, followed by the detection, using autoradiographic techniques, of the beta particles produced from the radioactive decay of the tritium trapped in sites of fatigue damage.

Autoradiography is a photographic technique by which radiation emanating from a body may be detected (Knoll (1989)). The main idea is that the specimen is infused with a radioactive isotope and the decay of the isotope is then detected using photographic emulsion techniques. One of the applications of autoradiography is to the study of hydrogen embrittlement of metals. The isotope most often used in these investigations is tritium, which is a radioactive isotope of hydrogen, and decays to helium by emitting a negative beta particle (i.e. an electron),

$$^3_1\text{H} \rightarrow ^3_2\text{He} + \beta^-.$$
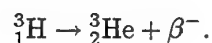
Tritium has similar properties to hydrogen, and both are therefore trapped in identical regions in the microstructure. It can thus be used to trace the concentration and distribution of hydrogen within metals. Evidence from investigations of hydrogen embrittlement suggests that common trap sites for tritium include grain boundaries, matrix interfaces, inclusion interfaces and dislocation boundaries. Saitoh *et al* (1994) charged tritium and hydrogen into specimens of pure aluminium, Al– 1 mass % Mg_2Si alloy and Al– 4 mass % Cu alloy, using a cathode charging method. A sensitive photographic film containing a layer of fine AgBr grains was adhered to each of the specimens and exposed to the beta rays emitted from the tritium in the samples. The film was developed and the resulting micro-autoradiographs were examined *in situ* with the specimens using a transmission electron microscope. The results of these experiments showed that for the pure aluminium and Al– 1 mass % Mg_2Si alloy, the dislocations act as traps for the tritium and are therefore revealed in the autoradiograph. Similar results were also obtained by Iijima *et al* (1992) who studied an Al– 6 mass % Zn– 2 mass % Mg alloy. These results suggest that it may be possible to utilise this technique as a means of detecting fatigue induced damage such as regions of high dislocation concentration and, perhaps, microcracks.

Tritium emits beta particles having energies ranging from 3.6 keV to a maximum energy of 18.61 keV, which are relatively low and consequently the particles have poor penetration ability. In fact these particles are stopped by as little as 4.5 mm of air (Caskey (1981)) or 0.01 mm of paper (Kaplan (1987)). As a result, beta radiation is difficult to detect and a photographic detection system must be used on or very close to the surface of the specimen.

There are several possible autoradiographic techniques which can be used, two of which are described below. The first is known as contact autoradiography. The specimen containing the tritium is placed in direct contact with a dry photographic plate. This is a macro-technique and is useful for obtaining information about the distribution and concentration of tritium within the specimen. After exposure the plate is removed from the specimen and developed.

The second technique is known as electron micro-autoradiography and involves a liquid emulsion. The photographic emulsion is developed whilst still in contact with the specimen

and the resulting autoradiograph is examined using either a scanning or transmission electron microscope. This technique is suitable for studying tritium distributions on a microscopic scale, for example, looking at tritium distribution between phases and boundaries, or looking at the area of high dislocation concentration just ahead of a crack tip. An explanation of other related techniques is described by Caskey (1981).

4. Summary and Conclusions

The concept of being able to apply a passive fatigue sensor to a structure is an attractive one, but some significant hurdles need to be overcome before it can be realised. The fundamental problem is one of satisfactorily relating the damage experienced by such a sensor to the damage suffered by the structure to which it is attached. The '-S/N-' fatigue life gauge (Harting (1966)) is a specific example that serves to illustrate the general problem. It is also a good case to discuss since the gauge was one of the first commerically available fatigue sensors and consequently received serious evaluation by a number of research organisations, including the Naval Air Development Centre. They commissioned a study, undertaken by Rosenfeld & Scheindlinger (1972), into the potential use of these gauges in high performance military aircraft. Rosenfeld & Scheindlinger (1972) examined the response of the gauges to both constant and variable amplitude fatigue loading when bonded in the vicinity of a stress concentrator in a fatigue specimen. The primary criterion used to assess the effectiviness of the gauges was that "a specific percent resistance change should indicate the same amount of damage experienced, within reasonable tolerance, regardless of the stress history". In experiments, under both constant and variable amplitude conditions, the 'tolerance' was found to be unreasonable. Apart from a high rate of premature gauge failure, that is the gauges failing due to fatigue well before the structure, the resistance change at specimen failure was found to vary considerably for nominally identical installations and experiments; in some cases by more than 100%. The authors concluded that it was not possible to reliably correlate a given percent resistance change with the actual fraction of specimen life expended. Possible reasons for the poor correlation were not given. However, the report did cite concerns held by the gauge producer about the inconsistency of manufacture of some of its gauges. Although this may provide part of the explanation, one can conceive a more fundamental problem that may shed light on the results found by Rosenfeld and Scheindlinger, and in broader terms, would provide a general reason for gauge ineffectiveness. The problem relates to the dissimilarity in materials between the gauge and the monitored structure. Materials accumulate damage in a manner that is particular to the microstructure and so even under nominally identical loading conditions, it is to be expected that different materials will accumulate damage in a different way and at different rates. In these circumstances, it would be possible to relate the damage in the gauge to the damage in the structure only if suitable calibrations had been performed. Whilst adequate calibrations may be feasible in the case of constant-amplitude type fatigue loading, it is questionable if the complex behaviours manifest by variable-amplitude loading (e.g. load-interaction effects on existing microcracks) could be effectively encompassed by calibration. These concerns relate equally well to the other fatigue monitors reviewed in this note, and indeed evidence showing calibration difficulties under variable amplitude loading may be found for some of these gauges, see for instance Nagase *et al* (1995) and Geissler & Gallagher (1983).

Despite these considerable problems, the development of an effective passive fatigue-damage monitor is still a realisable goal, and one that is well worth pursuing. The

mean-stress gauge concept developed at AMRL and described in this note should in principle offer a number of advantages over existing methods. However, several points need to be carefully considered in manufacturing these gauges to realise these advantages. The primary one is that the foil and the structure to which it is applied should be of the same material, and, if possible, of the same microstructure. This would increase the likelihood of the type and rate of damage accumulation being the same and ensure that the fatigue state of the gauge is representative of that of the structure. Careful attention should also be paid to the thickness of the foil. It should be thin enough to ensure it is subjected to the same strain as the structure, but sufficiently thick that it behaves in a manner that is similar to the structure; the optimal thickness could be determined by a combination of analytical stress-analysis and microstructural investigation. At the time this note was prepared, experiments were underway to assess the feasibility of the concept and the results of these will be reported at a later date.

All of the direct-inspection methods reviewed are capable of defect sensitivities that are sufficient for almost all fatigue monitoring purposes of engineering interest. They differ mainly in the difficulty involved in their practical application in the field. Some, like the positron annihilation technique seem suited more to laboratory-type investigations than to practical applications, while acoustic emission already has a history of application under field conditions. In the case of the tritium autoradiographic technique, experimental investigations are currently underway to assess its feasibility as an NDI method. The results of this investigation will be reported at the appropriate time.

ACKNOWLEDGEMENTS

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2. TITLE Methods of Early Fatigue Detection	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)

4. AUTHOR(S) N. Rajic and K. Tsoi	5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001

6a. DSTO NUMBER DSTO-TN-0059	6b. AR NUMBER AR-009-903	6c. TYPE OF REPORT Technical Note	7. DOCUMENT DATE October 1996

8. FILE NUMBER M1/9/186	9. TASK NUMBER DST 93/130	10. TASK SPONSOR DSTO	11. NO. OF PAGES 22	12. NO. OF REFERENCES 58

13. DOWNGRADING/DELIMITING INSTRUCTIONS None	14. RELEASE AUTHORITY Chief, Airframes and Engines Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

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16. DELIBERATE ANNOUNCEMENT

No limitations

17. CASUAL ANNOUNCEMENT	Yes

18. DEFTEST DESCRIPTORS

Fatigue (Materials); Detection; Damage; Metals

19. ABSTRACT
This note presents a brief review of techniques which may be applied to the detection of the early manifestations of fatigue damage in metals and also introduces two new methods which at the time of the preparation of this note were the subject of feasibility investigations at AMRL. In the first of these new methods, the fatigue state of a structure is inferred from variations in the electrical resistance of a metal foil bonded to the structure and subjected to the same loading history. The second method involves the infusion of radioactive hydrogen (tritium) into a structure that may contain fatigue damage. Damaged parts of the structure act as preferred trapping sites for the tritium, and these may be detected by the emission of beta radiation from the decay of the trapped tritium.